

Glassy Behavior in a Two-Dimensional Electron System ▀IHRP▴

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It is well known that the competition between strong electron-electron interactions and disorder leads to glassy dynamics (electron or Coulomb glass) and associated slow relaxation phenomena. More recently, field-theoretical studies have suggested¹ that glassy freezing may be crucial even in the critical regime of the metal-insulator transition (MIT). For two-dimensional (2D) systems, in particular, it is now well established that the MIT occurs in the regime where both electron-electron interactions and disorder are strong. It has been proposed, therefore, that a 2D MIT can be described alternatively as the melting of the Wigner glass², or the melting of the electron glass.³ It is thus clear that understanding the nature of the insulator and the study of the glassy behavior represents one of the crucial issues in this field.

We have studied the conductivity σ of a 2D electron system in Si metal-oxide-semiconductor field-effect transistors (MOSFETs) with a peak mobility of only ~ 0.1 m²/Vs at 4.2 K. For a 1 μ m long, 90 μ m wide rectangular sample, we have carried out detailed measurements of σ as a function of time for electron densities n_s ranging from 3.6×10^{11} cm⁻² to 20.2×10^{11} cm⁻², and at different temperatures $0.13 \leq T \leq 0.8$ K. The average conductivity σ_{av} and the root mean square deviation $\text{rms}(\delta\sigma)$ were obtained for fixed time intervals $\Delta t = 10, 5, 3, \dots$ hours. We find that conductivity fluctuations $\text{rms}(\delta\sigma)/\sigma_{av}$ increase dramatically below a certain density n_{sg} and temperature $T_g(n_{sg})$ (Fig. 1). Above $T_g(n_{sg})$, $\text{rms}(\delta\sigma)/\sigma_{av}$ are small and independent of T . Below $T_g(n_{sg})$, we observe long relaxation times and history dependent behavior characteristic of a glassy phase. These glassy phenomena become more pronounced with decreasing n_s and T . $\sigma_{av}(n_s, T)$ has been also analyzed in detail. The results that are available so far seem

to suggest that, in the $T \rightarrow 0$ limit, the onset of glassy behavior takes place in the metallic phase, *i. e.* at $n_{sg} > n_c$, where n_c is the critical density for the MIT. This is consistent with recent theoretical predictions.⁴ However, further experiments are needed to clarify in detail the relationship between the onset of glassy behavior and the 2D MIT. In particular, studies of systems with varying degrees of disorder would be helpful.

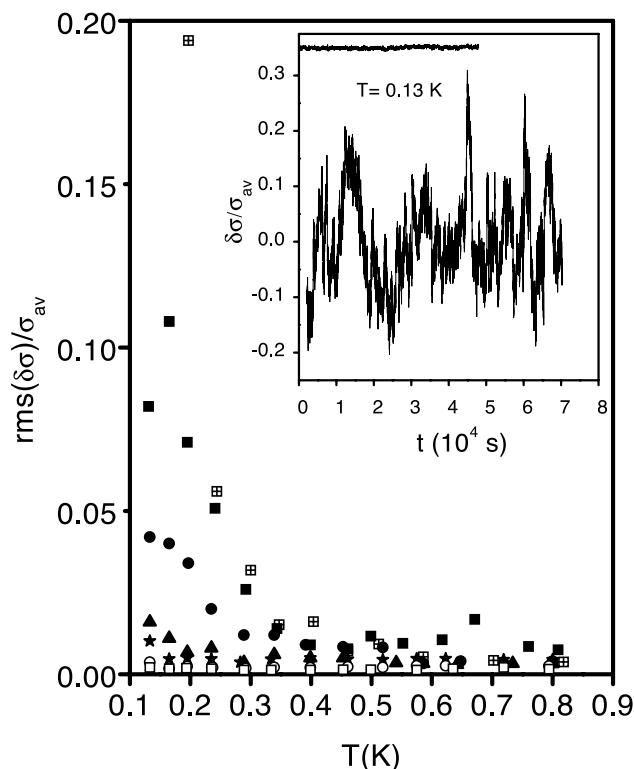


Figure 1. Conductivity fluctuations $\text{rms}(\delta\sigma)/\sigma_{av}$ vs. T for $n_s = 3.64, 3.86, 5.15, 6.01, 6.44, 6.87, 7.31 \times 10^{11}$ cm⁻² (top to bottom). At the lowest $n_s = 3.64 \times 10^{11}$ cm⁻², $\text{rms}(\delta\sigma)/\sigma_{av}$ reach more than 50% at $T = 0.13$ K (not shown). Inset: $\delta\sigma/\sigma_{av} = (\sigma - \sigma_{av})/\sigma_{av}$ as a function of time for $n_s = 3.86$ (lower trace) and 7.74×10^{11} cm⁻² (upper trace) at $T = 0.13$ K. The upper trace has been shifted up by 0.35 for clarity.

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- ¹ Belitz, D., *et al.*, Rev. Mod. Phys., **66**, 261 (1994); Phys. Rev. B, **52**, 13922 (1995).
- ² Chakravarty, S., *et al.*, Phil. Mag. B, **79**, 859 (1999).
- ³ Pastor, A.A., *et al.*, Phys. Rev. Lett., **83**, 4642 (1999).
- ⁴ Dobrosavljevic, V., *et al.*, (unpublished).

Polarized Spectroscopy of Dark Excitons in Semiconductor Nanocrystallites

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We report preliminary measurements of polarized photoluminescence spectroscopy of chemically-synthesized CdSe nanocrystallites in pulsed fields to 50 T. The nanocrystals are ~ 4 nm in diameter and highly monodisperse ($<10\%$ rms size variation), representing nearly ideal zero-dimensional quantum dots (QDs) in which to study quantum-confined electronic and spin interactions. One manifestation of this quantum confinement is the greatly enhanced electron-hole exchange interaction, which leads to a pronounced exciton fine structure, wherein the lowest ground state is a nominally “dark” spin-2 exciton. Optically active (spin-1), or “bright” excitons lie much higher in energy (~ 5 meV). Extremely high magnetic fields are required to generate Zeeman energies which are commensurate with this intrinsic exchange energy scale ($50\text{ T} \sim 3\text{ meV}$ if $g=1$).

Previous studies at the NHMFL have established that the high field polarization of the emitted photoluminescence from CdSe QDs is strongly circularly polarized, indicating a strong Zeeman splitting of the dark exciton ground state, as well as mixing with the higher lying optically active states.¹ However, the polarization never exhibits full, 100% polarization, due (largely) to the random orientation of the quantum dot c-axes (the nanocrystallites have wurtzite crystal structure).

To attain higher polarizations and clearly elucidate the exciton fine structure, we attempt to align the c-axes of the dots by drying the solutions in the presence of a large electric field. Fig. 1 shows the measured photoluminescence polarization from a sample of unaligned QDs, as well as a sample of QDs dried under an 8 kV/cm electric field. The data show a pronounced circular polarization, in agreement with previous measurements,¹ but demonstrate little, if any, preferred alignment (the polarization is still far from unity, even at the highest fields). Further

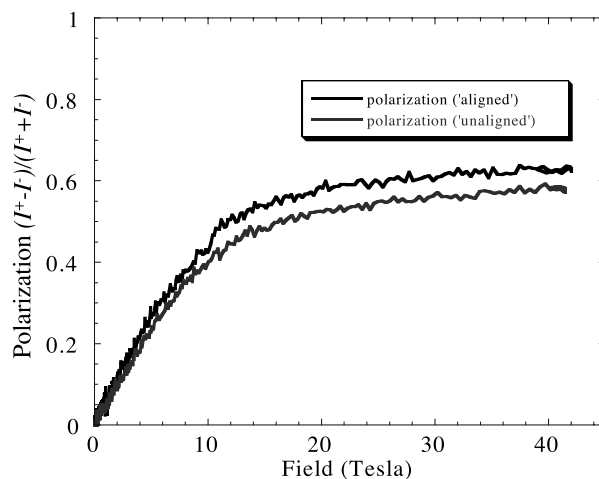


Figure 1. Degree of circular polarization of the photoluminescence from CdSe nanocrystallites. $T=1.5\text{ K}$.

efforts will include casting the dots in a slow-drying polymer matrix, and application of higher electric fields using semitransparent metal contacts.

¹ Johnston-Halperin, E., *et al.*, submitted to Phys. Rev. B (2000).

Pulsed Field Optical Spectroscopy of Negatively Charged Excitons in ZnSe-based 2D Electron Gases

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Semiconductor heterostructures based on wide-bandgap II-VI compounds, such as ZnSe, have long been investigated as a possible route towards green and blue semiconductor lasers. While this goal remains elusive, much interesting physics has been revealed in these material systems. In particular, the highly ionic nature of the II-VI compound semiconductors leads to greatly enhanced Coulomb interactions between electrons and holes as compared with more conventional III-V semiconductors such as GaAs. As such, many-body correlations in ZnSe-based semiconductor heterostructures containing 2D electron gases (2DEGs) are readily apparent. One such manifestation is the formation of the negatively charged exciton, consisting of a single photohole

bound to two electrons. In ZnSe, the binding energy of the second electron is of order 6 meV (compared with ~ 1 meV in GaAs-based structures). In this study, we investigate the formation and evolution of charged exciton bound states in single ZnSe-based quantum wells containing 2DEGs of varying electron density.

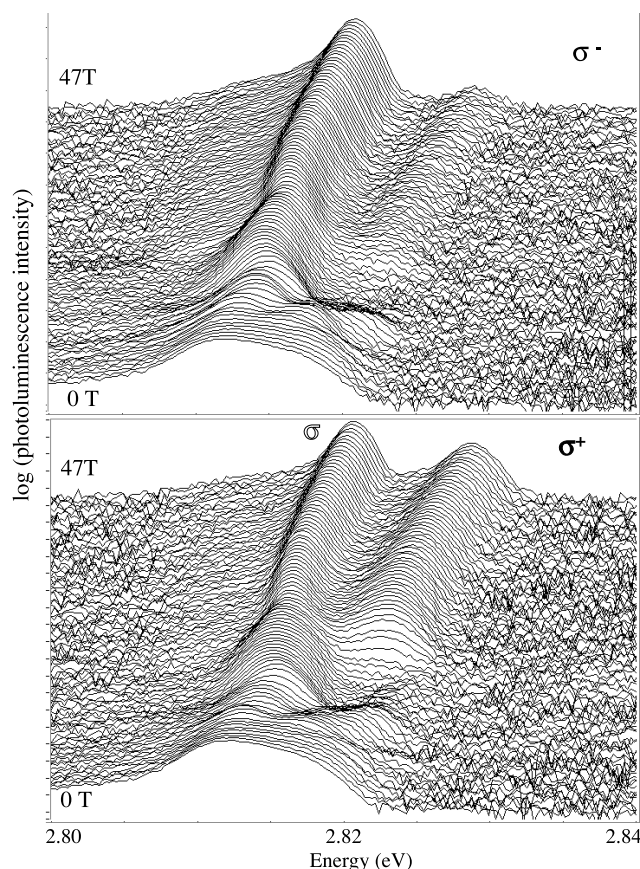


Figure 1. Polarized photoluminescence spectra from a ZnSe-based 2DEG ($n_e = 7 \times 10^{11} \text{ cm}^{-2}$) at 1.5 K in both (right- and left-handed) circular polarizations.

Fig. 1 shows the detected photoluminescence (PL) spectra at 1.5 K from a ZnSe quantum well containing $\sim 7 \times 10^{11}$ electrons/ cm^2 . The logarithm of the PL spectra are shown to enhance small features in the data. The data were taken in the new 50 T mid-pulse magnet, which provides a long, 300 ms pulsewidth. *In-situ* thin-film circular polarizers enable polarization analysis into right- and left-handed circular polarizations. As shown, the data reveal a rather broad PL peak at low fields, characteristic of recombination from the continuum of 2DEG states. With increasing field, the spectra exhibit Landau-level formation and then break up into excitonic peaks whose amplitudes and center wavelengths are

polarization-dependent. Particularly interesting are the formation of two clear peaks in σ^+ polarization, which may indicate the formation of both negatively charged (at lower energy), as well as neutral excitons (at higher energy). Similar features exist in the σ^- polarization, although the effect is much weaker. Further temperature-dependent studies will elucidate the nature of these features.

Resistance Spikes at Transitions Between Quantum Hall Ferromagnets

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We studied the properties of high-mobility electrons in AlAs quantum wells. AlAs electrons, with a higher effective mass than in GaAs, are more dilute and therefore more sensitive to Coulomb interactions, which makes them attractive candidates for the observation of new two-dimensional electron physics. Their g-factor is also larger than GaAs,¹ so that their Zeeman and cyclotron energies become comparable for a wide range of applied parallel and perpendicular fields.

We performed tilted-field magnetotransport measurements in samples with electron mobilities up to $20 \text{ m}^2/\text{Vs}$. As we changed the total field at a fixed tilt angle, we observed several phase transitions between quantum Hall states (“ferromagnets”) with different partial spin polarizations (Fig. 1A). We report here the appearance, at low carrier densities, of hysteretic resistance spikes at these phase transitions (Fig. 1B and Fig. 1C).² We also suggest that these spikes are caused by scattering at the edges of magnetic domains formed at the phase transitions.

Our samples are 150 Å-wide AlAs quantum wells grown within AlGaAs insulating barriers and on (411)B and (100) GaAs substrates. Experiments

were performed in $^3\text{He}/^4\text{He}$ dilution refrigerators at fields up to 18 T. Samples were fitted with a back gate and mounted on a single-axis rotating stage. Carrier density ranged from 1.6 to $5 \times 10^{11} \text{ cm}^{-2}$, tuned with a combination of back-gate capacitive bias and sample illumination.

The resistance spikes we observed spanned a large range of filling factors, densities, and magnetic fields.

The generality of their occurrence may help better quantify the exchange energies involved in Landau-level crossings, and thus give insight into the broader problem of dilute itinerant-electron ferromagnetism.

Acknowledgements: This research was supported by an NSF grant.

¹ Papadakis, S.J., *et al.*, Phys. Rev. B, **59**, R12743 (1999).

² De Poortere, E.P., *et al.*, Science, **290**, 1546 (2000).

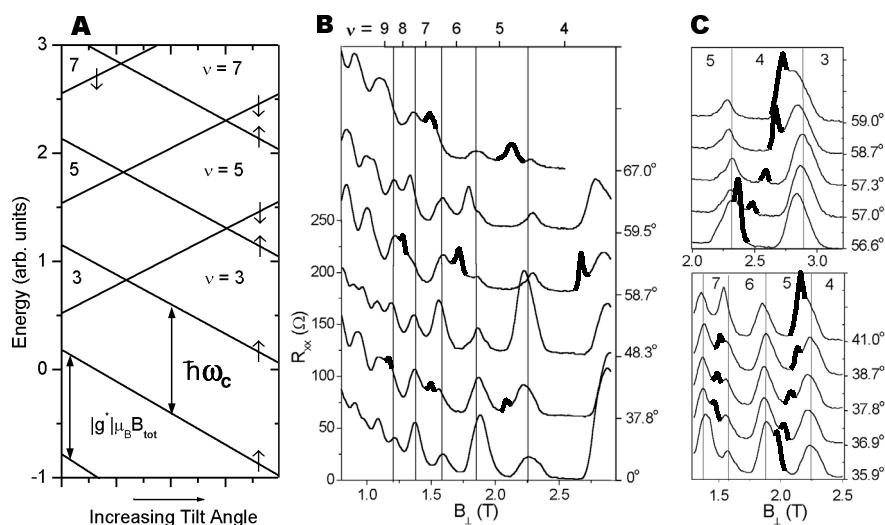


Figure 1. (A) Diagram of the Landau energy levels in a 2D electron gas, showing the spin-up and spin-down levels intersecting as parallel field (or angle θ) is increased. (B) Magnetoresistance of the 2D electron gas at $n=2.5 \times 10^{11} \text{ cm}^{-2}$ for various tilt angles at $T=30 \text{ mK}$. New peaks are seen near $\nu=5, 7$, and 9 for $\theta=37.8^\circ$ and $\theta=67.0^\circ$ and near $\nu=4, 6$, and 8 for $\theta=58.7^\circ$. R_{xx} traces are shifted vertically for clarity. Baselines ($R_{xx}=0$) are marked by the right tick marks, which indicate the corresponding tilt angle. (C) Movement of the peaks from higher to lower filling as tilt angle increases.

Effects of a Parallel Magnetic Field on the Unusual Metallic Behavior in Two Dimensions ▀ IHRP ▴

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In two dimensions (2D), the existence of a metal with an “insulating-like” temperature dependence of conductivity ($d\sigma/dT > 0$) is very surprising as it contradicts any theoretical description available to date. All the research efforts in recent years have considered only the metallic behavior with $d\sigma/dT < 0$. On the other hand, we have recently reported¹ the observation of a novel 2D metallic

behavior in Si metal-oxide-semiconductor field-effect transistors (MOSFETs). In this regime, the conductivity decreases as $\sigma(n_s, T) = \sigma(n_s, T=0) + A(n_s)T^2$ (n_s – carrier density) to a non-zero value as $T \rightarrow 0$. This simple $\sigma(T)$ spans two decades in T ($0.020 \leq T < 2 \text{ K}$). Our samples are representative of a broad class of Si MOSFETs historically known as “non-ideal” samples.² Our data strongly suggest the existence of a metallic phase at $T=0$ and of a novel, *continuous* metal-insulator transition (MIT) in 2D.

We have studied the effects of a parallel magnetic field B on the metallic behavior in these “non-ideal” MOSFETs for $0 \leq B \leq 18 \text{ T}$ and $0.020 \leq T < 2 \text{ K}$. $\sigma(n_s, T)$ was measured for many different fixed values of B . For each B , the critical density $n_c(B)$ was identified as the density where $\sigma(n_c, T) \sim T^x$, in agreement with our earlier work¹ and general scaling ideas.³ We have mapped out a phase diagram in the $(n_s, B, T=0)$ plane (Fig. 1), and found that the boundary between

metallic and insulating phases is described by a *power-law* relation $n_c(B) - n_c(0) \propto B^\beta$ at low fields, as expected from general arguments.³ The crossover exponent $\beta \approx 0.8$ for the two samples studied. At higher fields ($B > 1-2$ T), $n_c(B)$ seems to saturate.

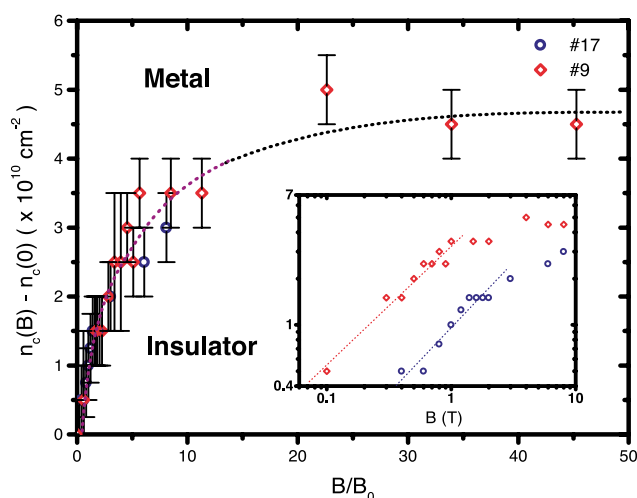


Figure 1. Phase diagram at $T=0$ for two samples. The dashed line guides the eye. The boundary between metallic and insulating phases is described by a power-law relation (see inset) $n_c(B) - n_c(0) = (B/B_0)^\beta$ at low fields, with the same exponent β for both samples. Inset: the same data vs. B on a log-log scale. The dashed lines are linear least squares fits with the slopes (exponent β) equal to 0.80 ± 0.06 and 0.84 ± 0.09 for samples 9 and 17, respectively.

Magnetoconductance, $\sigma(B)$, was obtained both from the above measurements and from magnetic field sweeps for a fixed n_s and T . The behavior of $\sigma(B)$ is consistent with the phase diagram shown in Fig. 1. In particular, at relatively high n_s (deep in the metallic phase), $\sigma(B)$ decreases weakly with B .⁴ We find that the metallic phase is not destroyed even in fields of up to 18 T. On the other hand, very near the $B=0$ MIT, an exponentially large drop of magnetoconductance (MC) is observed with increasing B .⁴ A detailed analysis of $\sigma(n_s, T, B)$ shows⁵ that the characteristic field that describes the rapid drop of MC is related to the critical magnetic field at which the MIT occurs for a given n_s (see Fig. 1).

Our data provide strong evidence for the existence of a metal-insulator transition in these 2D systems, which is unlike any other known quantum phase transition in 2D. Experiments in tilted magnetic fields

will be carried out in order to gain further insight into the nature of this 2D conducting phase and into the origin of the simple, well-defined $\sigma(T)$ that is observed in these “non-ideal” MOSFETs.

Acknowledgements: This work was supported by an NHMFL In-House Research Program grant and NSF grant DMR-0071668.

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- ² Ando, T., *et al.*, Rev. Mod. Phys., **54**, 437 (1982), and references therein.
- ³ Belitz, D., *et al.*, Rev. Mod. Phys., **66**, 261 (1994).
- ⁴ Eng, K., *et al.*, to be published in the Proceedings of the 25th International Conf. on the Physics of Semiconductors.
- ⁵ Eng, K., *et al.* (unpublished).

Recombination Mechanisms in ZnMnSe(n)/AlGaAs(n)/GaAs/AlGaAs(p) Spin LEDs

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We have investigated the recombination mechanisms for ZnMnSe/AlGaAs/GaAs/AlGaAs spin LEDs using magnetoluminescence spectroscopy. In these devices, the n-type ZnMnSe layer acts as a spin filter that selects the $m_s = -1/2$ electron spin state due to the large conduction band spin splitting (10 meV at 3 T) of the DMS layer. As a result, the electroluminescence (EL) is strongly circularly polarized as σ_+ .¹ The band-edge EL spectra can be classified in the following three categories:

- (1) EL spectra contain free and bound excitonic features
- (2) EL spectra contain a broad electron-hole (eh) recombination feature accompanied by bandgap renormalization, with no excitons present

- (3) Mixed. Both excitonic and (eh) recombination features are present.

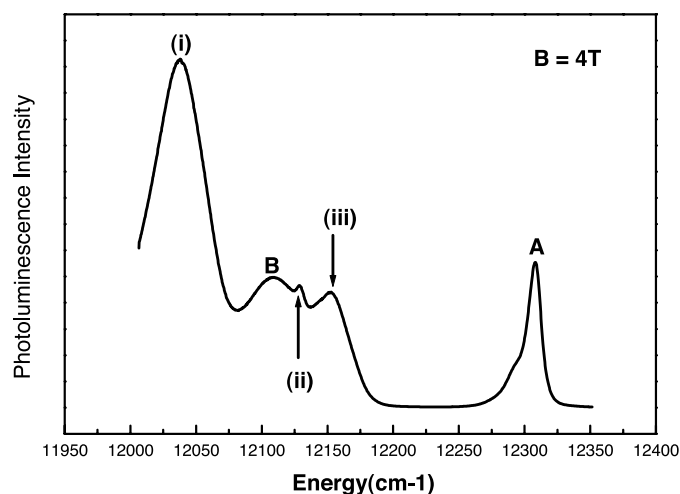


Figure 1. Photoluminescence spectra at B=4 T from a GaAs/AlGaAs spin LED.

We have used magnetoluminescence spectroscopy to compare the energy dependence of the PL excitonic and (eh) features in a type (3) spin LED. The magnetic field dependence of the excitonic feature (feature A) energy shows a typical diamagnetic shift, which identifies it unambiguously. On the other hand, the energy of the (eh) recombination (feature B) has a linear dependence on magnetic field with a slope of $8 \text{ cm}^{-1}/\text{T}$. The EL and PL spectra indicate that the GaAs well in which recombination takes place is inhomogeneous and contains areas in which a dense electron gas is present. The (eh) recombination feature is associated with such regions. In addition, there are areas depleted of carriers that are responsible for the excitonic features. Features (i), (ii), and (iii) are tentatively attributed to phonon replicas of the exciton that become activated by disorder at the GaAs/AlGaAs interfaces.

Acknowledgments: This work was supported by the Office of Naval Research and the Defense Advanced Research Projects Agency SpinS program.

¹ Jonker, B.T., *et al.*, Phys. Rev B, **62**, 8180 (2000).

NMR Lineshape Analysis of Chalcogenide Glasses

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In semiconductors that are disordered, the local and intermediate range structural order are difficult to characterize by the usual x-ray, neutron, or electron scattering techniques. In glassy semiconductors, the lack of structural order makes it very difficult to probe on a range greater than the nearest neighbor distance. In cases such as these, nuclear magnetic resonance (NMR) can be a very useful probe, especially when the nucleus is subjected to a large quadrupole interaction with the field gradient of the electric field at the nuclear site.^{1,2,3,4}

Recently, we have developed a technique to analyze the high field NMR lineshapes of chalcogenide glasses where quadrupole broadening of the NMR lineshape is very large.^{5,6} In this report we describe our analysis of high field NMR lineshapes of glassy $\text{As}_{0.5}\text{Se}_{0.5}$ at 77 K. Fig. 1 shows the nuclear quadrupole resonance (NQR) lineshape of glassy $\text{As}_{0.5}\text{Se}_{0.5}$ at 77 K. The vertical lines correspond to NQR frequencies in both As_2Se_3 and As_2Se_4 . For crystalline As_2Se_4 , which has the same composition as $\text{As}_{0.5}\text{Se}_{0.5}$, each As atom has one As-As bond. As a result, NQR frequencies in this crystal are much higher than those in crystalline As_2Se_3 . The entire NQR lineshape can be decomposed into three gaussian functions A, B, and C, as shown in Fig. 1. By comparison with the NQR frequencies in the crystals, we can identify curve A as the signal due to As atoms with one As-As bond, curve B as signal from two As-As bonds and curve C as that due to As sites bonded to three selenium atoms. The presence of different bonding configurations in glassy $\text{As}_{0.5}\text{Se}_{0.5}$ suggests that the bonding configuration in the glass is not determined by chemical ordering. Instead, statistical fluctuations are important.

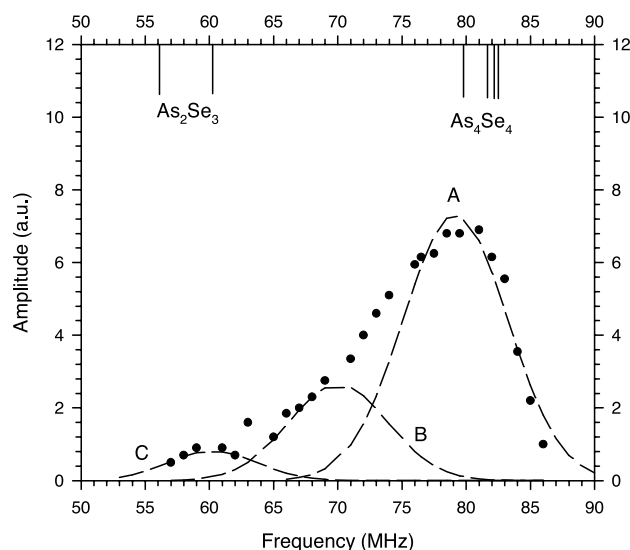


Figure 1. NQR lineshape of glassy $\text{As}_{0.5}\text{Se}_{0.5}$ at 77 K is shown here. Solid circles represent raw data. The dashed lines represent the decomposition of the lineshape. The dashed curves A, B, and C are decomposed lineshapes for the arsenic sites with one, two, and zero As-As bonds. The solid lines represent the NQR frequencies in the crystal.

Our detailed analysis suggests that in glassy $\text{As}_{0.5}\text{Se}_{0.5}$, the bonding configuration depends on both chemical ordering and statistical fluctuations.⁷ Based on the analysis of NQR lineshape, the ^{75}As NMR lineshape is fitted with two different values of the asymmetric parameter η for the three different configurations as shown in Fig. 2a and b. The value of η for site A, B, and C are respectively 0.6 and 0.16. For the arsenic sites with no As-As bonds, the value of η is very close to that in glassy As_2Se_3 , which is stoichiometric. This result is further evidence of a statistical influence on the bonding configurations. Also, η is much larger for the As sites with one As-As bond. This difference enables us to clearly distinguish the two different bonding configurations, i.e., the sites with one As-As bond and the sites with no As-As bonds.

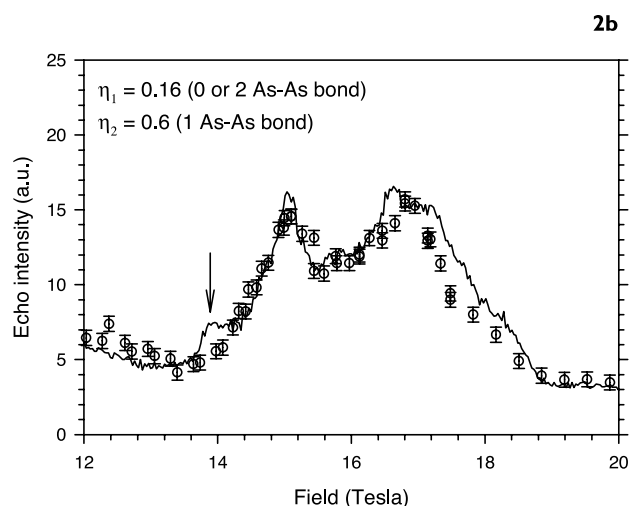
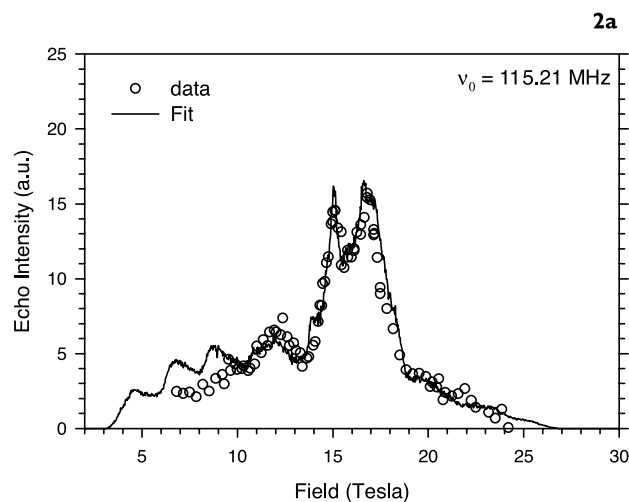


Figure 2a and b. ^{75}As NMR lineshape in $\text{As}_{0.5}\text{Se}_{0.5}$ at high field is (Fig. 2a) fitted with two different values of η for the three different bonding configurations is shown in Fig. 2b. From Fig. 1, the values for asymmetry parameters η are 0.16 for curves B and C and $\eta = 0.6$ for curve A.

- ¹ Szeftel, J., *et al.*, Phys. Rev. Lett., **42**, 5274 (1979).
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- ⁶ Hari, P., *et al.*, Non-Cryst. Solids, **227-230**, 770 (1998).
- ⁷ Hari, P. *et al.*, in preparation (2001).

Resonant Coupling of Cyclotron and Spin Resonances in Modulation-Doped CdMnTe/CdMgTe Quantum Well Structures

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We have studied an electron-electron interaction in the unique situation when cyclotron and spin resonances cross, i.e., when two neighboring Landau sublevels with opposite spins are degenerate. In order to realize experimentally such a case, we took advantage of the giant spin-splitting present in diluted magnetic semiconductors (DMS) in magnetic fields. Far infrared (FIR) transmission of a modulation-doped DMS (CdMnTe) quantum well has been measured. The CdMnTe well was embedded in nonmagnetic CdMgTe barrier material. The FIR measurements were carried out at 4.2 K in the Faraday configuration at magnetic fields up to 17 T. The quantum well contained 2.2% of Mn ions and the concentration of two-dimensional electrons was $3 \times 10^{11} \text{ cm}^{-2}$.

At magnetic fields lower than 7 T and higher than 13 T, we observed a single resonance (CR) line. Between 7 T and 13 T, a spin-flip resonance (SFR) appears in the spectra. Both lines are very narrow—their line widths do not exceed 4 to 6 cm^{-1} , which allows them to be resolved even when they are separated by less than 3 cm^{-1} , as at $H=8$ T. The narrow line width confirms the high mobility of the 2DEG (on the order of $105 \text{ cm}^2/(\text{Vs})$) in agreement with transport data.¹ We fit the experimental data by a theoretical model proposed by Fal'ko² taking into account the giant spin splitting in DMS quantum well material. In Fig.1, the two resonance lines are clearly distinguished—the CR energy depending linearly on magnetic field and the SFR with more complex field dependence. The best fit was obtained for the effective mass of 2DEG of $0.114 m_0$ in agreement with previous data.³ The saturation value of the spin splitting (78 cm^{-1}) gives the Mn content in the well ($x=2.15 \%$).

The most intriguing result is the non-zero value of the splitting energy between the two energy branches shown in Fig. 1. The energy gap equals to $E_g=2.5 \text{ cm}^{-1}$. The result clearly shows that the CR and SFR are resonantly coupled by the spin-orbit interaction given by the parameter E_g . As predicted by the theory, the spin-orbit interaction is enhanced at the crossing of $(0,\uparrow)$ and $(1,\downarrow)$ Landau levels. The spin-orbit interaction causes non-parabolicity of the band and allows the electron-electron correlations to be observable in the experiment.

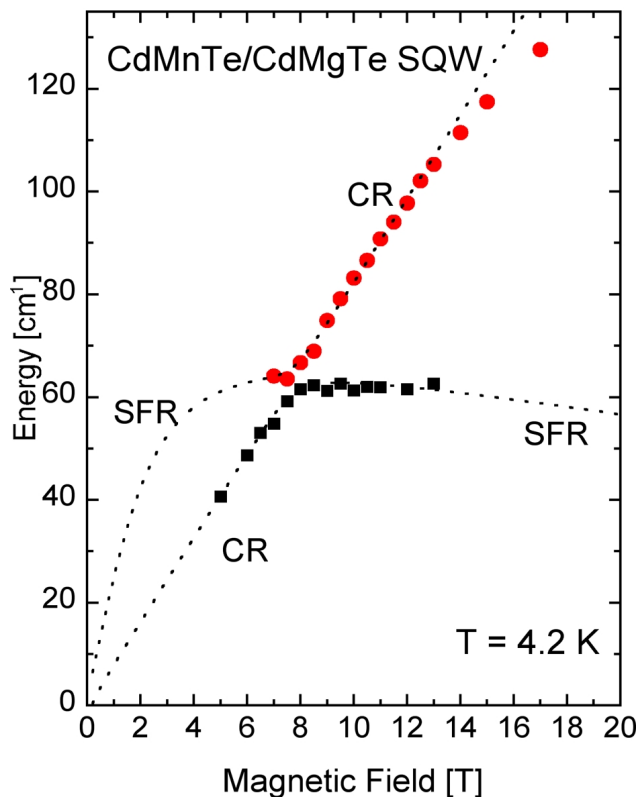


Figure 1. Energy positions of the observed resonance lines in a function of magnetic field. The high-energy branch is shown by circles and the low-energy one by squares. The solid lines represent the best fit of Fal'ko's theory.¹

Acknowledgements: G.K. would like to express his gratitude to the Fulbright Foundation for supporting his investigation at the NHMFL in Tallahassee.

¹ Karczewski, G., *et al.*, J. Crystal Growth, **184/185**, 814 (1998).

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³ Imanaka, Y., *et al.*, Physica B, **256-258**, 457 (1998).

High Magnetic Field Studies of AlGaIn/GaN Heterostructures

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We performed high magnetic field (to 30 T) studies of the transport properties of the two-dimensional electron gas (2DEG) in AlGaIn/GaN heterostructures grown over high-pressure bulk GaN, sapphire, and insulating SiC substrates. The measurements were performed in a wide temperature range 1,6–300 K.

The room temperature high field measurements allow us to clearly separate the contributions of a parasitic parallel conduction from 2DEG conduction in all investigated heterostructures. It has been done by measurement and simulation of the conductivity tensor components (see Fig.1).

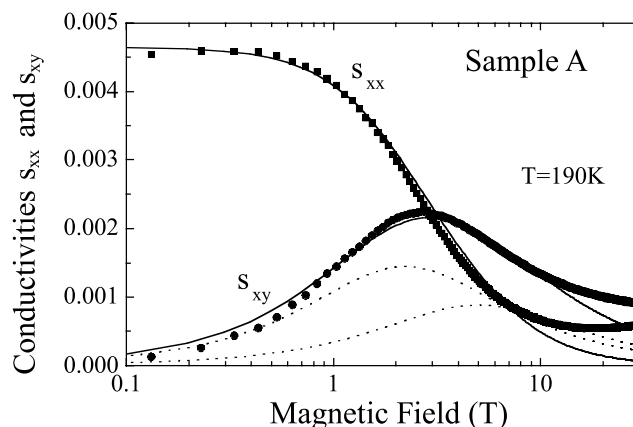


Figure 1. Components of the conductivity tensor for sample A at temperature 190 K, as a function of the magnetic field. Points correspond to experimental results. Lines are best fits, calculated in the two-carrier conduction model.

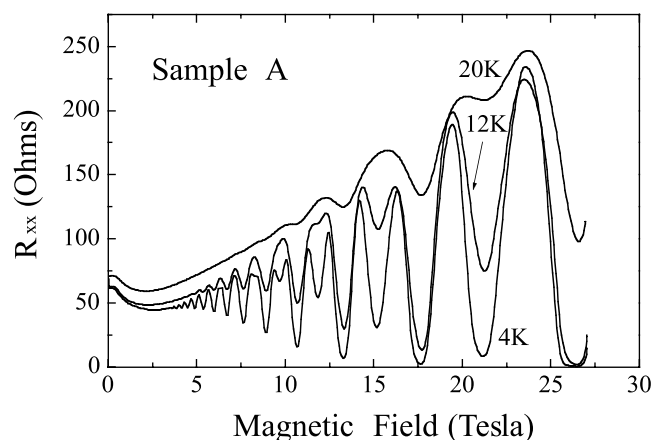


Figure 2. Shubnikov de Haas oscillations for different temperatures - sample A.

The magnetotransport measurements performed at low temperatures (below 100 K) in combination with very high mobilities (over 60,000 cm²/Vs at 2 K) in the sample on the bulk GaN substrates (sample A) allow us to observe features related both to cyclotron resonance and spin splitting. The temperature dependence of this splitting (see Fig. 2) determines the spin and cyclotron resonance energy gaps, and in combination with cyclotron resonance and tilted field experiments, allows us to determine the complete energy structure of the 2DEG conduction band. The first experimental results showing so called “exchange enhancement” of the energy gaps between spin Landau levels were obtained.

The results were partially presented in an Invited Talk at the MRS Fall Meeting–Boston 2000 and will be published in the proceedings.¹ The regular journal publication is in preparation.

¹ Knap, W., *et al.*, High Magnetic Field Studies of AlGaIn/GaN Heterostructures Grown on Bulk GaN, SiC, and Sapphire Substrates, MRS Fall Meeting Boston 2000 – www.mrs.org.

Plasma Waves Detection and Generation in Sub Micron High Electron Mobility Transistors

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Recent theoretical works have shown that plasma waves at terahertz frequencies can be generated in a two-dimensional electron gas confined in a sub micron field effect transistor,¹ which acts as a resonant cavity for the waves.

The frequency of the oscillations is defined by the electron concentration and the size of the resonant cavity. Plasma wave generation can be used for both emission and detection of THz electromagnetic radiation.

We investigated the detection of 100 GHz and 200 GHz radiation by sub micron High Electron Mobility Transistors (HEMT's). The main goal of these first experiments was to check if THz radiation coupling to the sub micron HEMT's is strong enough to allow for detection. We found that for 100 GHz and 200 GHz generated by a Gunn oscillator and a Gunn oscillator associated to a doubler can be registered using lock-in techniques with signal to noise ratio of greater than 10. This allowed us to investigate the photoconductivity of the sub micron HEMT's as a function of the gate voltage. A typical result is shown in Fig.1. We found that the functional dependence

of the signal is reasonably well reproduced by the theory in Ref. 2. This result confirms the predictions that it is possible to detect THz radiation using plasma waves in the sub micron HEMT's.

Using magneto transport experiments simultaneously with detection experiments, we could determine the mobility and carrier density in the HEMT channel. We found from these parameters that the devices were operated far from the resonant frequency that was determined to be in the range 300 GHz to 600 GHz. We are planning experiments in these spectral regions. We are also currently testing HEMT's based on the GaN/AlGaIn hetero junctions that are expected to have resonant frequencies below 300 GHz—well adapted to sources existing in NHMFL.

¹ Dyakonov, M., *et al.*, Physical Review. Letters., **71**, 2465-2468 (1993).

² Weikle, R., *et al.*, Electronics Letters, **32**, 7, 2148-2149 (1996).

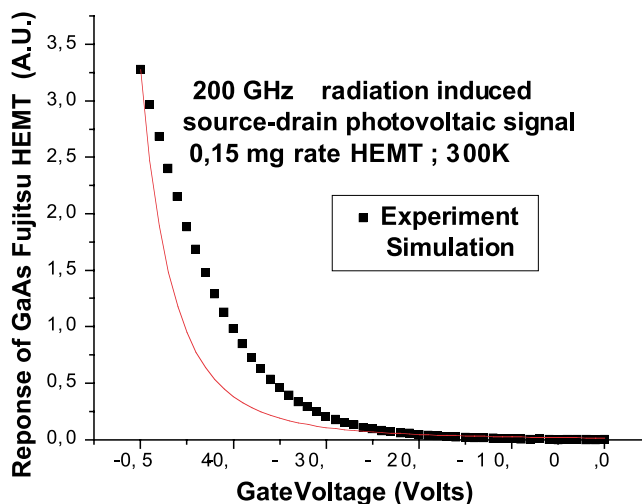


Figure 1. Radiation induced source-drain photo voltaic signal as a function of the gate voltage.

Chiral Edge States of Weakly Coupled Multilayered GaAs/AlGaAs Quantum Wells at Low Temperatures with Finite In-Plane Field



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This study follows a previous investigation¹ of the nature of transport in multiple quantum well structures (MQW), where the quantum Hall effect (R_{xx} and R_{xy}) and the interplane (chiral edge state) transport (R_{zz}) were studied as a function of tilted magnetic fields. The main findings from Ref. 1 were: (a) complete quantization of all 200 quantum wells was observed, even in the presence of finite interplane coupling of the wells, (b) even in the presence of complete quantization, a finite dissipation remained in the in-plane R_{zz} for $T > 0$, and (c) for tilted magnetic fields, where an in-plane component develops, the quantization first improved (i.e., the Hall plateaus widened, and R_{zz} decreased), but then rapidly degraded above about 30° . This last finding is at odds with our current theoretical understanding of the chiral edge state model in multiple layer QHE systems. Likewise, the degradation of the quantization goes against the conventional wisdom that the QHE will improve with in-plane field due to improved confinement of the 2DEG electronic wave function. Indeed, for a single quantum well with the same architecture, we found that the quantization is insensitive to increasing in-plane field² for angles up to 50° .

The purpose of the present study was to measure R_{zz} for a new MQW system where the interplanar coupling is less due to an increased GaAlAs barrier thickness between the GaAs quantum well layers. The mesa samples were processed at the Nanofabrication Laboratory at the University of New South Wales. Representative data is shown in Fig. 1 where R_{zz} has been studied vs. angle at 30 mK. The most

pronounced maximum in R_{zz} appears for the $\nu=2$ QHW state. Larger values of R_{zz} correspond to a more complete transition to “ideal” chiral edge state/quantized transport. We find that, as for the case for the more strongly coupled sample, the quantization is a maximum at finite angles (here 10°), and then degrades with further increase in angle (i.e., increasing in-plane field). In contrast, we note that a new state, which corresponds to a $\nu=5/3$ Landau level filling, appears, and becomes **enhanced** with increasing in-plane field.

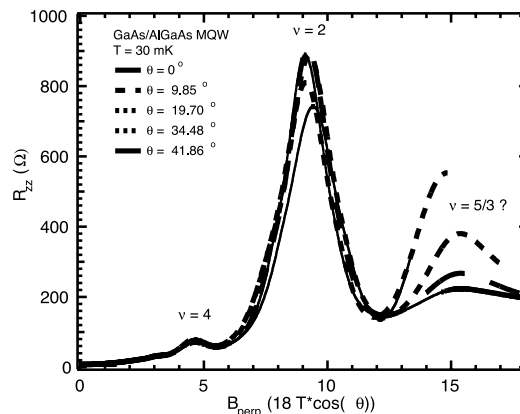


Figure 1. Interplane resistance R_{zz} vs. magnetic field normal (B_{perp}) to the conducting MQW planes for increasing in-plane magnetic field ($B_{\parallel}=0$ T, 3.08 T, 6.06 T, 10.19 T, 12.0 T). The peak in R_{zz} for $\nu=2$ decreases above $B_{\parallel}=3.0$ T. For filling factor $\nu=5/3$, the peak increases monotonically over the same range of B_{\parallel} .

Our results show that the finite dissipation observed in coupled MQW structures in the IQHE (integer) state, together with the degradation of the IQHE above an optimum in-plane field, are a general feature of these supposedly chiral systems. However, for the FQHE (fractional) states, finite in-plane field appears to improve the quantization. Further work is in progress to understand the details of the FQHE phenomenon.

Acknowledgements: The authors acknowledge support from IHRP/NHMFL 501, NSF-DMR 95-10427 and 99-71474 (JSB). The NHMFL is supported through a cooperative agreement between the State of Florida and the NSF through NSF-DMR-95-27035.

¹ Zhang, B., *et al.*, Phys. Rev. B, **60**, 8743-8747(1999), and references therein.
² Matson, J., *et al.*, to be published.

High Magnetic Field Spectroscopy of Negatively Charged Excitons in CdTe 2D Electron Gases

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We have studied the charged excitonic optical transitions of two dimensional electron gases (2DEGs) at $T=1.6$ K using polarization resolved photoluminescence (PL) and reflectivity up to 60 T, and time-resolved PL up to 18 T. The samples are CdTe/(Cd,Mg)Te modulation doped quantum wells (QWs) of 75 Å, 100 Å and 200 Å width. The electron densities are estimated about $4.4 \times 10^{11} \text{ cm}^{-2}$ from the maximum of PL intensity at the filling factor $\nu=2$. The current interest in the study of negatively charged exciton in high magnetic field is supported by recent theoretical works predicting a crossover between the spin-singlet state (X_s^- , total spin $S=0$) and a spin-triplet state (X_t^- , $S=1$) with magnetic field.¹ However, the triplet states observed at high magnetic field² lies at higher energy than the singlet. New calculations on GaAs quantum wells suggest that two triplet states with different orbital momentum may be bound at finite field: a “bright” state (X_{bt}^-) and a non-radiative “dark” ground state³ (X_{dt}^-).

Fig. 1 shows the evolution of the PL peaks in the case of the 100 Å 2DEG. Below 20 T ($\nu=1$) the PL spectra show only the X_s^- recombination. By extrapolating the positions of the s^+ and s^- PL peaks to zero magnetic field, we obtain a surprisingly large g-factor for X_s^- : $g \approx 2.3$ (instead of the expected $g \approx 0.75$ for the neutral exciton) which doesn't change significantly with the QW width. Above 20 T, the X_s^- peak is damped in σ^+ polarization according to the filling factor $\nu=1$. The most important observation is the abrupt decrease of the X_s^- peak in σ^- polarization around 35 T with the appearance of a weak peak at lower energy. Such behavior is also observed at lower field (25 T) for the 200 Å 2DEG. We do believe that these balances of optical recombination are a signature of the ground state transition between the singlet and the dark triplet states. The evolution

with the magnetic field of their binding energy are in good qualitative agreement with the calculations of Wojs, *et al.*

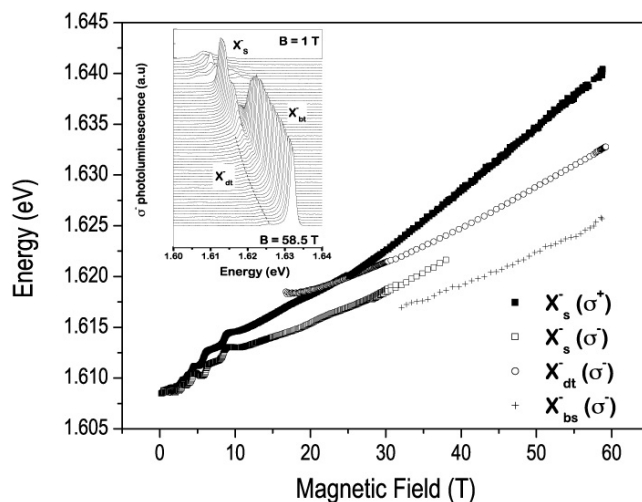


Figure 1. Positions of the PL peaks observed at 1.6 K for the 100 Å CdTe 2DEG. The inset shows the PL spectra in σ^- polarization from 1 T to 58.5 T in steps of 1 T.

¹ Whittaker, D.M., *et al.*, Phys. Rev. B, **56** 15185 (1997).

² Hayne, M., *et al.*, Phys. Rev. B, **59** 2927 (1999).

³ Wojs, A., *et al.*, Phys. Rev. B, **62** 4630 (2000).

Oscillations in the Cyclotron Resonance in Modulation-Doped ZnSe/Zn_{1-x-y}Cd_xMn_ySe Single Quantum Wells ▀IHRP▴

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The cyclotron resonance (CR) of a two-dimensional electron gas in modulation-doped ZnSe/Zn_{1-x-y}Cd_xMn_ySe single quantum wells (SQW) has been measured using Fourier Transform spectroscopy in magnetic fields up to 31 T. This report concentrates on detailed measurements of two samples, the magnetic sample, Zn_{0.94}Cd_{0.05}Mn_{0.01}Se, and the non-magnetic analogue, ZnSe/Zn_{0.94}Cd_{0.06}Se. The samples have carrier densities of 1.3 and $1.8 \times 10^{11} \text{ cm}^{-2}$ respectively and mobility of $\sim 16,000 \text{ cm}^2/\text{V}\cdot\text{s}$ for both samples. Our results show that the amplitude and line-width (scattering lifetime) of the CR absorption

show strong oscillatory behavior with the periodicity governed by the Landau filling factor, ν . In addition, the effective mass shows both polaron effects and has a maximum at the filling factors.

Figures 1(a) and (b) show the effective mass and the full-width at half-maximum of the CR absorption plotted as a function of filling factor. It is clear from the figures that the mechanisms that give rise to the filling factor play a dominant role in the oscillations. For both samples and for $\nu < 1$, the rise in the effective mass is due to the coupling to the LO phonon line—the polaron mass enhancement. Since II-VI semiconductors have large Fröhlich electron-phonon interaction constants, α , ($\alpha_{\text{ZnSe}}=0.42$, $\alpha_{\text{CdSe}}=0.45$) the bare effective mass has a polaronic correction for photon energies $\hbar\omega < \hbar\omega_{\text{LO}}$. In the 2-D case, the mass enhancement goes as $1/8 \pi\alpha$ whereas in the 3D the enhancement is smaller and has $1/6 \alpha$ correction.

Band non-parabolicity and screening also affect the effective mass. The first correction can be estimated using a two-band $\mathbf{k}\cdot\mathbf{p}$ approximation where the conduction and valence bands are separated by an energy gap E_g . In this case the corrections term goes as $2\hbar\omega_c/E_g$. Since the band gap is large for our samples ($E_g(\text{CdSe}) = 1.77$ eV and $E_g(\text{ZnSe}) = 2.82$ eV) this correction is much smaller than the polaronic correction. In the Thomas-Fermi approximation the electron-gas screening increases with increasing electron density. For a low density semiconductor the screening can be neglected. In the high field regime and for $\nu < 1$ screening is not expected to play a significant role. However, screening manifest itself in the vicinity of the filling factor, as we shall discuss next.

The oscillations in the effective mass, line widths, and amplitudes can be understood by the change in screening resulting from the change in the density of states at the Fermi level with ν . Here, the long range potential is reduced by screening since the static polarizability of the electron gas is directly proportional to the density of states at the Fermi level, E_F . This implies that the screening is large if E_F lies at the center of the Landau level and small if E_F is at the edge. When the screening is large, the effective mass is small as the electron-phonon

coupling is reduced. This also results in smaller line-width (longer lifetime) since there is less scattering with the ionic sites.

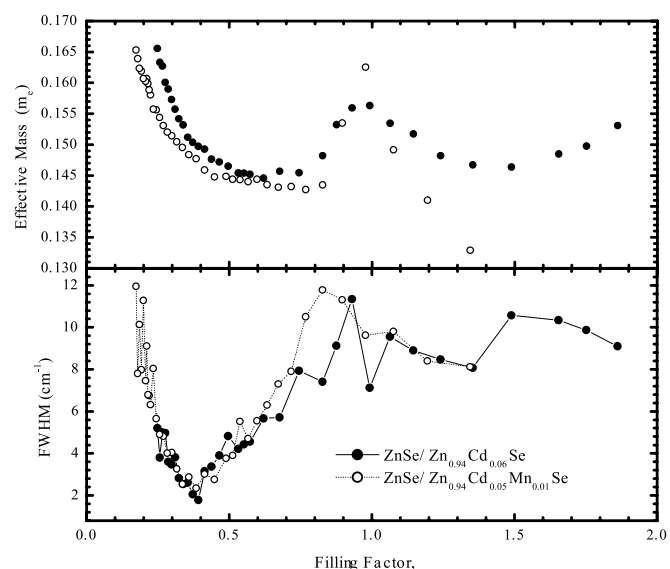


Figure 1. (a) Effective mass as a function of filling factor. (b) Half-width at half-maximum of the CR absorption line.

Perhaps the most interesting result is the significantly lower mass in the magnetic sample compared to the non-magnetic sample for $\nu > 1$. This region, which corresponds to fields less than 7 T, is the subject of considerable debate as to the mechanisms that cause this decrease. For dilute magnetic semiconductor samples with low electron density, magnetoresistivity measurements show a peak in the ρ_m/ρ_0 plot. This feature will be investigated further.

Acknowledgment: Work at FSU is supported in part by the State of Florida through the Center for Materials Research and Technology, and the NHMFL In-House Research Program, and the NHMFL's NSF contract (DMR-9527035). The authors wish to thank N. Samarth for providing the samples.

Mechanism of Electrically Detected Electron Spin Resonance in the Regime of the Quantum Hall Effect

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Although very little is known about the mechanism of electrical detection of electron spin resonance (EDES) in GaAs quantum wells, one possibility is that a simple bolometric effect is responsible; i.e. a change in the temperature of the electron system caused by the resonant absorption of microwaves. An alternative explanation is that the EDES results from microwave induced changes in the spin-dependent scattering, a model that has been employed to explain EDES signals outside of the QHE regime in Si MOSFET systems. Toward the goal of understanding the mechanism of EDES in the regime of the QHE, the temperature (see Fig.) and filling factor dependence (not shown) of the EDES response near $\nu=1$ was measured. An expression for the temperature dependence of the EDES response based on the bolometric model will be derived here. This simple model will be compared with the data to address the basic question of whether or not the EDES mechanism is consistent with a bolometric effect. Thermal activation of magnetoresistance is a common method for measuring the energy gap $\Delta = m\hbar\omega_c + \Delta m_s g\mu_B B_0 + \Delta_c(k, B_0)$ associated with magnetoplasmons ($m=1$) and spin waves ($m=0$, $\Delta m_s=1$), where ω_c is the cyclotron frequency, $g\mu_B B_0$ is the single electron Zeeman energy, and $\Delta_c(k, B_0)$ is the energy contribution due to electron-electron Coulomb interactions. It is important to note that only $k \rightarrow \infty$ excitons contribute to the thermally activated magnetoresistance, where $R_{xx} = R_0 \exp(-\Delta/2T_e^{eq})$, while ESR involves $k=0$ transitions with $\Delta_c(k=0, B_0)=0$ due to Kohn's theorem.

In the proposed bolometric model, the temperature change in the electron system is induced by the resonant absorption of microwave energy due to ESR excitations. The microwave field acts on the electron system (neglecting non-resonance effects) by increasing its spin-temperature, T_s . In our simple model the electron spin polarization is taken to be $p_z^{eq} = \tanh(E_z/T_s^{eq})$, where E_z is the energy gap between the spin levels and T_s^{eq} is the equilibrium spin temperature. Now consider the spin-lattice relaxation of the electron spins as they absorb energy from the resonant microwave field. If the electron spin temperature equilibrates with the electron temperature, then setting $T_s = T_e$ will be justified. The resistance change induced by the resonant microwaves in this model becomes a function of Δ, E_z, T^{eq} and S . The model function is plotted against temperature using $\Delta=6.8$ K assuming an arbitrary saturation parameter $S=0.1$ and several values of E_z . The value $E_z = g\mu_B/k = 1.72$ K corresponds to the bare g-factor of the independent electron system and $E_z = 6.8$ K corresponds to the fully exchange-enhanced g-factor. The model corresponding to the independent electron Zeeman gap ($E_z = 1.72$ K) exhibits a clear maximum, while the EDES response based on the exchange enhanced gap ($E_z = 6.8$ K) reaches a plateau as $T \rightarrow 0$. The occurrence of a maximum in $\Delta R_{xx}(T)$ at approximately 2 K is in qualitative agreement with the data only if $E_z < \Delta$. This conclusion remains valid for any arbitrary value of the saturation parameter.

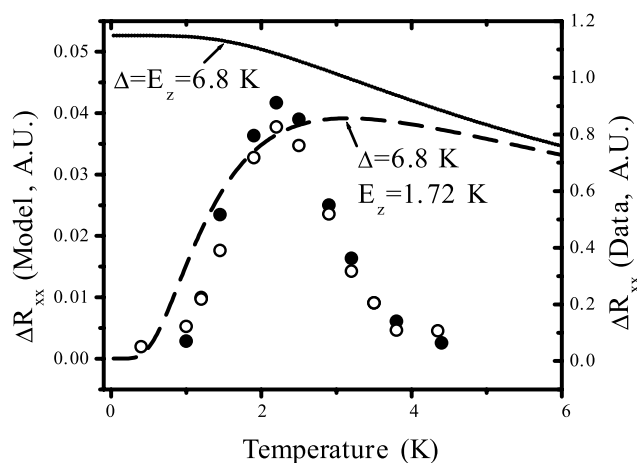


Figure 1. Temperature dependence of EDES peak area. *Open symbols:* down sweep, *filled:* up sweep. The dotted and dashed lines are plots of the model described in the text.

Angular Dependent Measurements of the $\nu = 5/2$ Fractional Quantum Hall Effect State at Ultra-Low Temperatures

■ IHRP ■

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The spin polarization of the even-denominator fractional quantum Hall effect (FQHE) state at $\nu=5/2$ remains an open, but important question to answer. One method of addressing this question is to measure the angular dependence of the energy gap. Since the energy gap at $\nu=5/2$ is rather small, this kind of experiment is technically extraordinary challenging, due to the requirement of *in situ* rotation of the sample at ultra-low temperatures. We constructed a rotator made from polycarbonate, which operated hydraulically using liquid ^3He . It worked extremely well down to the lowest temperatures. Details of its design and operation will be published elsewhere. To our knowledge, this is the first rotator that operates below 10 mK. The rotation of the sample is monitored by the magnetic field position of resistance minimum at $\nu=5/2$. It depends only on the perpendicular magnetic field, $B_{\text{perp}} = B_{\text{total}} \times \cos(\theta)$, where B_{total} is the total field and θ is the tilt angle.

A sequence of experiments at ultra-low temperatures clearly demonstrated the possibility of performing angular-dependent measurements at such extreme conditions, although we have not yet been able to deduce the spin polarization of the FQHE state at $\nu=5/2$ from these data. However, the same run allowed us to measure in detail the FQHE states to

around the $\nu=7/2$ sister state of the $\nu=5/2$ state. For the first time, we were able to identify the FQHE states at $\nu=10/3$ ($3+1/3$), and $11/3$ ($3+2/3$) around $\nu=7/2$ (Fig. 1). This demonstrates that the major fractions around $\nu=7/2$ are indeed of the $p/3$ type, confirming the picture of electron-hole symmetry in the second Landau level. Strong resistance minima are also observed at the filling factors $\nu=16/5$ ($3+1/5$), $19/5$ ($3+4/5$), and $23/7$ ($3+2/7$). With such an exceptionally high quality sample, we should be able to address the spin polarization in the near future.

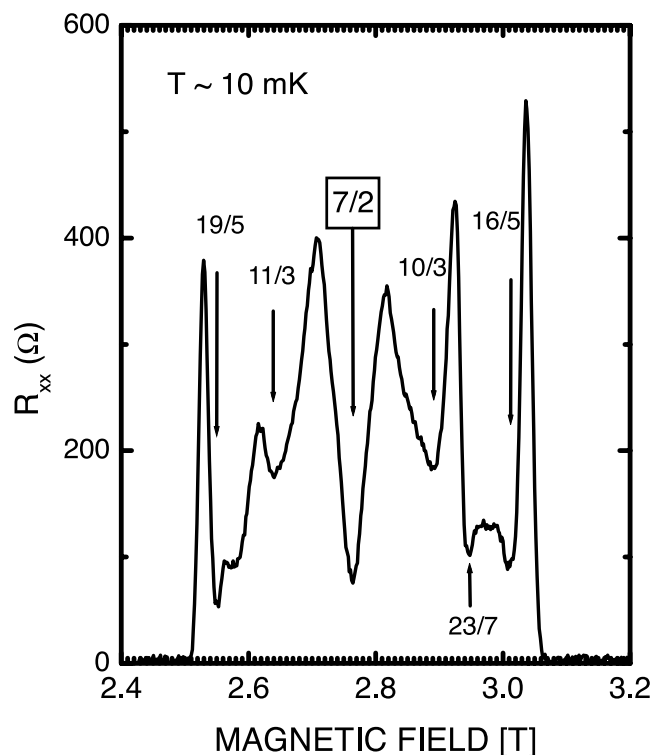


Figure 1. Magnetoresistance R_{xx} around $\nu=7/2$ at $T \sim 10$ mK. Major FQHE states are indicated by arrows.

Reorientation of Anisotropy at $\nu=9/2$ and $11/2$ in a Square Well Quantum Hall Sample Under a Tilted Magnetic Field

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Most recently, strongly anisotropic transport has been observed in high quality GaAs/Al_xGa_{1-x}As samples at filling factors $\nu=9/2$, $11/2$, etc. In these experiments, the magnetoresistance shows a strong peak in one current direction and a deep minimum in the perpendicular current direction. Tilting the magnetic field, \mathbf{B} , away from the sample normal causes the high resistance direction to change from its original orientation to the in-plane magnetic field (B_{ip}) direction. The most appealing interpretation of this anisotropy suggests that the 2D electron gas spontaneously breaks the translational symmetry by forming a unidirectional charge density wave (UCDW).

A theoretical study,¹ in samples with two subbands occupied in zero magnetic field, has predicted much more complex behavior of the UCDW state, including stripe states induced by an in-plane field and rotation of stripe orientation at critical in-plane field strengths. A comparison between theory and experiment in a geometry for which this intricate behavior occurs, constitutes an excellent test of the UCDW explanation of anisotropic transport in higher Landau levels. We have thus chosen a square quantum well structure with two occupied electric subbands and measured magnetotransport at half-filled high Landau levels.² We find resistivities that are practically *isotropic* in

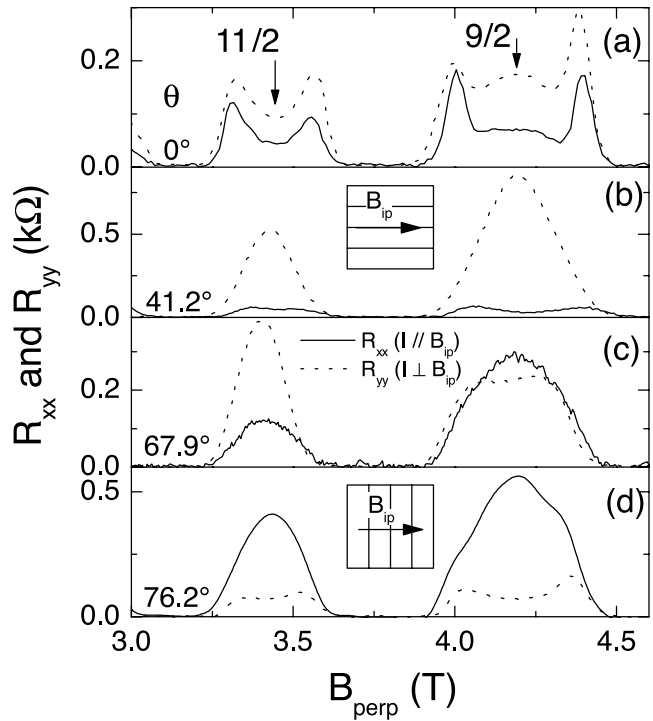


Figure 1. R_{xx} (solid line) and R_{yy} (dotted line) between $4 < \nu < 6$ at four tilt angles in a square quantum well with two occupied electric subbands.

perpendicular magnetic field, but become strongly *anisotropic* at $\nu=9/2$ and $11/2$ on tilting the field. The anisotropy appears at an in-plane field, $B_{ip} \sim 2.5$ T, with the easy-current direction *parallel* to B_{ip} , but rotates by 90° at $B_{ip} \sim 10$ T and points now in the “normal” direction (*perpendicular* to B_{ip}). This complex behavior is in quantitative agreement with theoretical calculations based on a unidirectional charge density wave state model.

¹ Jungwirth, T., *et al.*, Phys. Rev. B, **60**, 15574 (1999).

² Pan, W., *et al.*, Phys. Rev. Lett., **85**, 3257 (2000).

Bright and Dark Triplet States of the Negatively Charged Magnetoexcitons: Photoluminescence and Time-Resolved Measurements to 60 T ■ IHRP ▲

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Continuous and time-resolved magnetophotoluminescence (MPL) measurements of three asymmetrically-doped GaAs/AlGaAs quantum well nanostructures have been made in high magnetic fields to 60 T. The electron densities were $n=1.58 \times 10^{11} \text{ cm}^{-2}$ for a 20 nm single quantum well (SQW), and $2.1 \times 10^{11} \text{ cm}^{-2}$ and $2.5 \times 10^{11} \text{ cm}^{-2}$, respectively, for two single heterojunction (SHJ) samples. The MPL spectra revealed the presence of four distinct peaks as shown in Fig. 1. These peaks have been interpreted as a singlet (X_s^-), and two triplet states (the so-called “bright” (X_{tb}^-) and “dark” (X_{td}^-) states) of the negatively charged magnetoexcitons, in addition to one associated with the neutral exciton (X_0). For the SQW, the MPL peaks corresponding to the singlet and dark triplet states merged (and possibly crossed) at a field of about 40 T. This result was in good agreement with recent calculations by Whittaker and Shields (WH)¹ and by Wojs *et al.*² In contrast, the two SHJs showed no such convergence. In these two samples, the distance between the electrons and the non-localized holes is larger and their behavior is expected to be similar to that predicted for a wide SQW with the singlet remaining the ground state¹ at least to the highest fields investigated (60 T).

Observation of the normally optically inactive “dark” exciton (X_{td}^-) is assumed to be the result of asymmetry introduced into the samples through the carrier doping mechanism and the breakdown of Laughlin-Halperin correlations usually associated with wide quantum wells.² In the low field regime (0 to 20 T), the lifetimes of the charged magnetoexcitons increased

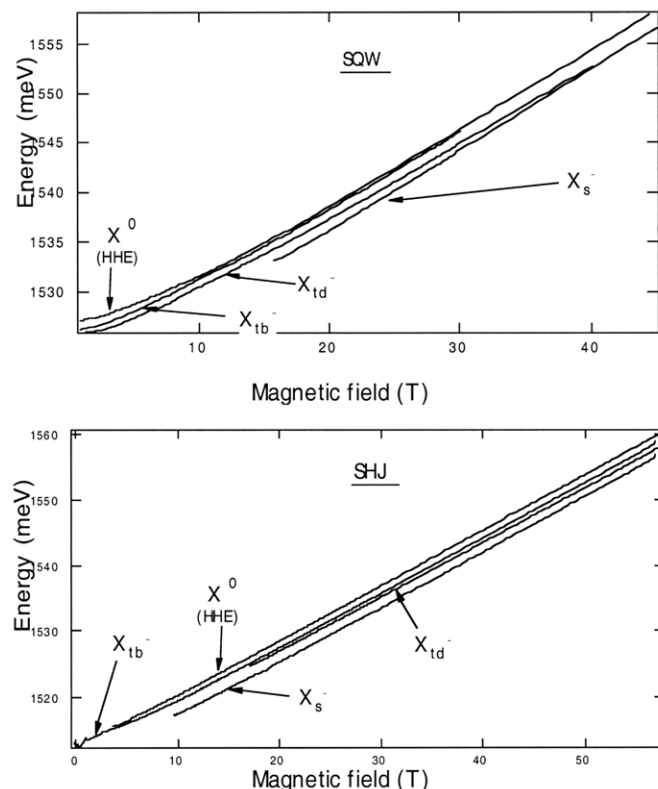


Figure 1. The four observed magnetoexciton peaks X_s^- , X_{td}^- , X_{tb}^- , and X_0 for (a) a 20 nm SQW and (b) a SHJ from 0-50 T. In (a), (SQW), the X_s^- and X_{td}^- merge in the 35 to 40 T range with X_{td}^- possibly becoming the ground state. In (b), (SHJ), no crossing of X_s^- and X_{td}^- is observed. In both cases, X_{tb}^- is the strongest transition at high fields and is located at an energy higher than X_{td}^- . The results are in good agreement with the calculations of WH¹ and Wojs *et al.*²

linearly with field, whereas the neutral exciton was essentially field independent. At high fields, all the lifetimes increased due to the stronger localization. The results clarify earlier experimental studies by this group³ and by others,⁴ and provide a confirmation of the theory of the behavior of charged magnetoexcitons in magnetic fields by WH¹ and by Wojs *et al.*²

¹ Whitaker, D.M., *et al.*, Phys Rev B, **56**, 15185 (1997).

² Wojs, A., *et al.*, Phys. Rev B, **62**, 4360 (2000); *ibid* Physica E, **8**, 254 (2000).

³ Munteanu, F.M., *et al.*, Phys. Rev. B, **61**, 4731 (2000); *ibid* Phys. Rev B, **61**, 4492 (2000).

⁴ Hayne, M., *et al.*, Phys Rev B, **59**, 2927 (1998).

Electron-Hole Separation Studies Near the $\nu=1$ Quantum Hall State in Modulation-Doped GaAs/AlGaAs Single Heterojunctions in High Magnetic Fields IHRP

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Magnetophotoluminescence studies, as a function of carrier concentration ($n_{2D}=2.2\text{--}7.2\times 10^{11}\text{cm}^{-2}$), are reported for a series of very high mobility ($>1.8\times 10^6\text{cm}^2/\text{V.s}$) n-type remotely doped GaAs/AlGaAs single heterojunctions (SHJs). The measurements were made in high magnetic fields to 60 T at temperatures in the 0.4–2.1 K range. At $\nu=2^-$, a strong excitonic transition (X_0) appears primarily in σ^- polarization due to a spin electron recombining with a valence band hole.^{1–3} It rapidly gains intensity between $2>\nu>1$, but disappears at $\nu=1^+$. At $\nu=1^-$, a new red-shifted transition emerges that has been described as a recombination of an electron in an initial “free hole state.” Its intensity in σ^- polarization increases and reaches a maximum between $1>\nu>1/3$. Examples of the red-shifts for two different samples are shown in Fig. 1.

Quantitative estimates can be made of the binding energy, spin wave energy, and the separation between the planes in which the electrons and holes move.^{1,2} In the limit of low electronic Zeeman energy (i.e. low magnetic field), the excitonic state in which a spin-down electron from the conduction-band (CB) is bound to a hole from the valence-band (VB) will be the fundamental state of the system. This will only occur if the distance, d_{e-h} , between the electron and hole planes is such that $d_{e-h} < 1.3l_c$, where l_c is the cyclotron radius. For larger values of d_{e-h} , the

excitonic state will no longer be the ground state. Its place will be taken by a transition where the valence hole binds to an electronic spin texture, in which more than one electron presents some degree

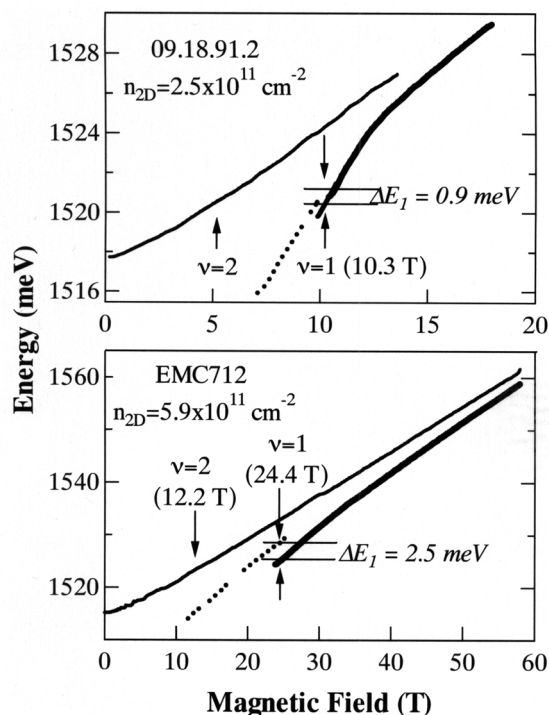


Figure 1. Observed transition energies for FX, X^0 , and the recombination to a free-hole state (F-HS) for two representative samples. Note the red-shifts at filling factors 1 and 2.

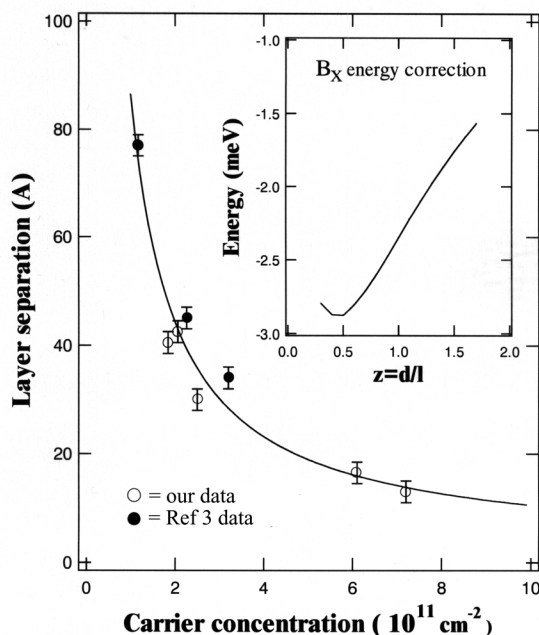


Figure 2. Plot of the electron-hole separation, d_{e-h} , as a function of carrier concentration. The inset shows the calculated exciton binding energy correction as a function of d/l .

of spin depolarization leading to the formation of an excitonic Skyrmion.

We used the relations derived by Cooper and Chklovskii¹/Hawrylak and Potemski² and included both a spin-wave and a binding energy correction in our calculations to obtain a direct estimate of the electron-hole separation, d_{e-h} , near the interface. We have obtained d_{e-h} as a function of the carrier concentration in these SHJs for $d_{e-h} > 1.3l_c$. In our analysis, we have also included data from Nicholas *et al.*³ who reported studies of MPL of SHJs with 2D carrier densities in the range of $0.7\text{--}3.2 \times 10^{11} \text{ cm}^{-2}$. To a good approximation, we found a $1/n_{2D}$ dependence of the electron-hole separation with carrier concentration as seen in Fig. 2.

¹ Cooper, N.R., *et al.*, Phys. Rev. B, **55**, 2436 (1997).

² Hawrylak, *et al.*, Phys. Rev. B, **56**, 12386 (1997).

³ Nicholas, R.J., *et al.*, Physica B, **249-251**, 538 (1998).

High Field NMR of Epitaxial Semiconductors

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High field NMR systems offer new opportunities to study a number of fundamental properties of compound semiconductors. For instance, III-V semiconductor materials form either as zincblende or wurtzite cubic structures where a number of the constituent atoms possess nuclei with an electric quadrupole moment. In the presence of applied magnetic field, the Hamiltonian H of a nuclear spin ($I > 1/2$) is expressed as: $H = H_Z + H_Q + H_D + H_E + H_{PD}$, where H_Z is responsible for Zeeman splitting, H_Q is the quadrupole term, H_D is the dipole term, H_E represents indirect exchange interaction by conduction electrons, and H_{PD} represents the pseudo-dipolar term. In the general case of any perfect cubic crystal, the quadrupole interaction H_Q is non-existent. However, imperfections that distort the cubic symmetry give rise to local electric field gradients that cause a quadrupole interaction. The shape of the observed NMR line then is determined by the magnetic dipole interaction with neighboring spins, plus the electric quadrupole interaction between the electric field gradient (EFG) and the quadrupole

moment of the nucleus. These quadrupole-gradient interactions vary not only in orientation but also in magnitude from site to site; hence, they influence the NMR line-shape considerably. Understanding these quadrupole interactions and their correlation to NMR line-shapes provides insight into the growth processes of compound semiconductors.

Utilization of high magnetic fields, where the Zeeman Hamilton is dominant and all others are treated as perturbations, allows for systematic studies of these perturbations. In the specific case of III-V semiconductors where the nuclei generally possess large quadrupole moments (an exception is ³¹P), the line broadening is dominated by the nuclear electric quadrupole/local EFG interaction. This interaction leads to a first order energy splitting of the central and satellite transitions according to:

$$E = \frac{e^2 q Q}{4I(2I-1)} (3m^2 - I(I+1))$$

where eq is the electric field gradient, eQ is the quadrupole moment, and $m = -I, -I+1, \dots, I$. Thus, to first order, the quadrupole interaction does not influence the central transition ($m = -1/2 \leftrightarrow m = 1/2$), but does influence the satellite transitions ($m = -3/2 \leftrightarrow m = -1/2$ etc...). In general the splitting may either be observable, or lead to characteristic line broadening. As preliminary studies, we have collected spectra on MOCVD grown epitaxial GaAs films on the 19.6 T solid state NMR system. The resonance frequency of ⁷⁵As at this field strength is 142.75 MHz. 5mm x 3 mm x 10 μm samples were first placed perpendicular to the static magnetic field, B_0 , then parallel. In the case where the sample was placed perpendicular to B_0 , the full width at half height (FWHH) of the central arsenic transition was 13.5 ppm. When the sample was rotated by 90 degrees, the FWHH increased to 16.3 ppm. Orientation dependent studies shed light on the nature of quadrupole-EFG interactions.

A thorough study of these effects contributes to our understanding of semiconductors, properties and growth, and the interplay between the two.

Observation of Integral and Fractional Quantum Hall Effects in AlGaIn/GaN Heterostructures

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We present results from electrical transport measurements on a two-dimensional electron gas (2DEG) in AlGaIn/GaN in high magnetic fields. The heterostructures consist of a 0.5 μm GaN layer followed by 30 nm of $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$, grown by molecular beam epitaxy (MBE) onto a 20 μm thick GaN template grown by hydride vapor phase epitaxy (HVPE) onto a sapphire substrate. Contacts were made with evaporated Ti/Al annealed at 530 $^{\circ}\text{C}$ for 15 minutes.

Longitudinal magnetoresistance measured with 1 microampere excitation current at $T \sim 500$ mK, exhibits Shubnikov-de Haas oscillations at about 1.5 T. Spin-splittings of Landau levels are resolved near 3.5 T, followed by the onset of well-defined quantum Hall states near 12 T. At higher fields, for the first time, we observe clear features of fractional quantum Hall states in this wide band gap material. A sample with $n = 1.16 \times 10^{12}/\text{cm}^2$ and $\mu \sim 20,000$ cm^2/Vs shows a clear minimum at filling factor $\nu = 5/3$ with a 35% drop in resistance. A second sample, with $n = 1.26 \times 10^{12}/\text{cm}^2$ and $\mu \sim 21,000$ cm^2/Vs , displays a 10% drop at the minimum for $\nu = 5/3$. A third specimen, with $n = 1.02 \times 10^{12}/\text{cm}^2$ and $\mu \sim 25,000$ cm^2/Vs shows clear evidence of fractional states at $\nu = 5/3$ and $\nu = 4/3$. Moreover, in all of the above cases where we see features in R_{xx} , we also observe inflections at the corresponding magnetic fields in the Hall data.

Evidence for the fractional quantum Hall states in AlGaIn/GaN 2DEG speaks for the tremendous improvement in the material quality of this relatively new wide-bandgap semiconductor system.

Transient Effects in the Cyclotron Resonance of a 2D Quantum Well

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We have started some preliminary investigations to study transient cyclotron resonance in 2-dimensional electron gases. Recently, some new theoretical models predict large changes in the cyclotron resonance line width as a function of frequency and field, and of the ratio of the Fermi energy with respect to random long-range potential fluctuations. Application of light to the system changes both line width and intensity of the cyclotron resonance. Previously, we performed cyclotron resonance measurements on quantum-well systems with and without continuous illumination. We have started to investigate the possibility of

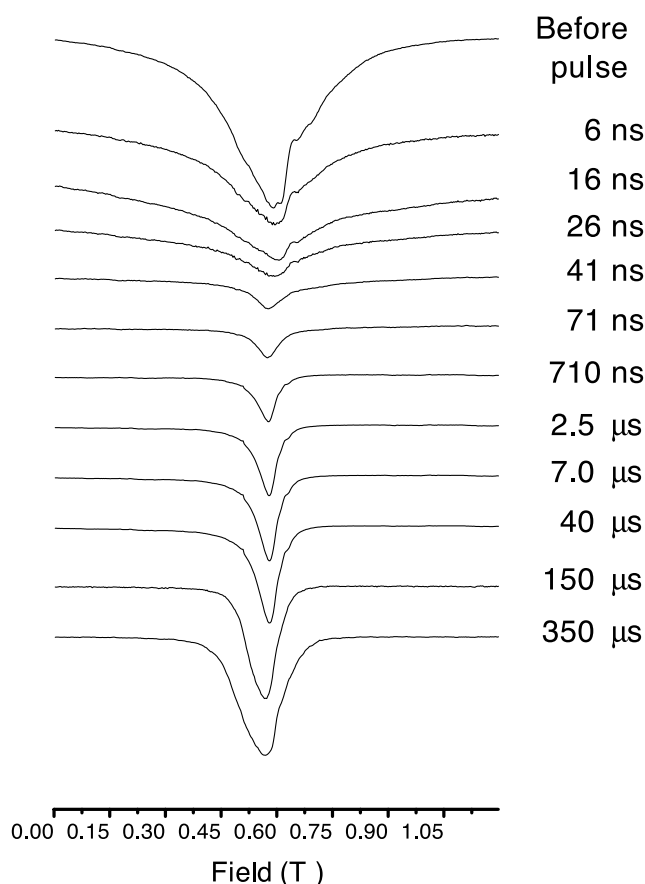


Figure 1. Reflection at 240 GHz of a GaAs/AlGaAs single quantum well as a function of field and time after a 532 nm laser pulse.

looking at the response of the system to a short light pulse in the new high field transient electron magnetic resonance spectrometer. The fast time resolution of the spectrometer allows us to measure in the ns-range during and shortly after the laser-pulse. The light intensity was kept low ($\sim 10 \mu\text{J}$), and illuminated the sample indirectly and uniformly. The accompanying figure shows the measured reflection of 240 GHz radiation from the GaAs:AlGaAs single quantum well sample as a function of the field and the time after the 532 nm laser pulse at 6 K. Directly after the pulse, the cyclotron line width broadens, but then after 30 ns it collapses to a much narrower resonance before broadening again to the intensity and line width that was measured before the laser pulse.

Though the limited experiments that were performed are as yet not fully understood, they show the capability of studying transient effects in the cyclotron resonance with very high time-resolution.

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Universal Conductivity of the 2D Electron System in Silicon MOSFETs in Strong In-Plane Magnetic Fields

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The magnetoconductance of the 2D electron system in silicon MOSFETs was measured as a function of in-plane magnetic fields H up to 18 T at different electron densities n (Fig. 1a). Except for data in a small region near $H=0$, an excellent collapse of all the magnetoconductance data of Fig. 1 (a) is obtained by applying two simple shifts (on a linear scale): a shift parallel to the σ or y -axis followed by a shift parallel to the H or x -axis. As shown in Fig. 1 (b), this yields a *universal* curve, $\sigma_H(H-H_{\text{SAT}})$ such that:

$$\sigma(n, H) = \sigma_H(H-H_{\text{SAT}}) + \sigma_{\text{SAT}}(n)$$

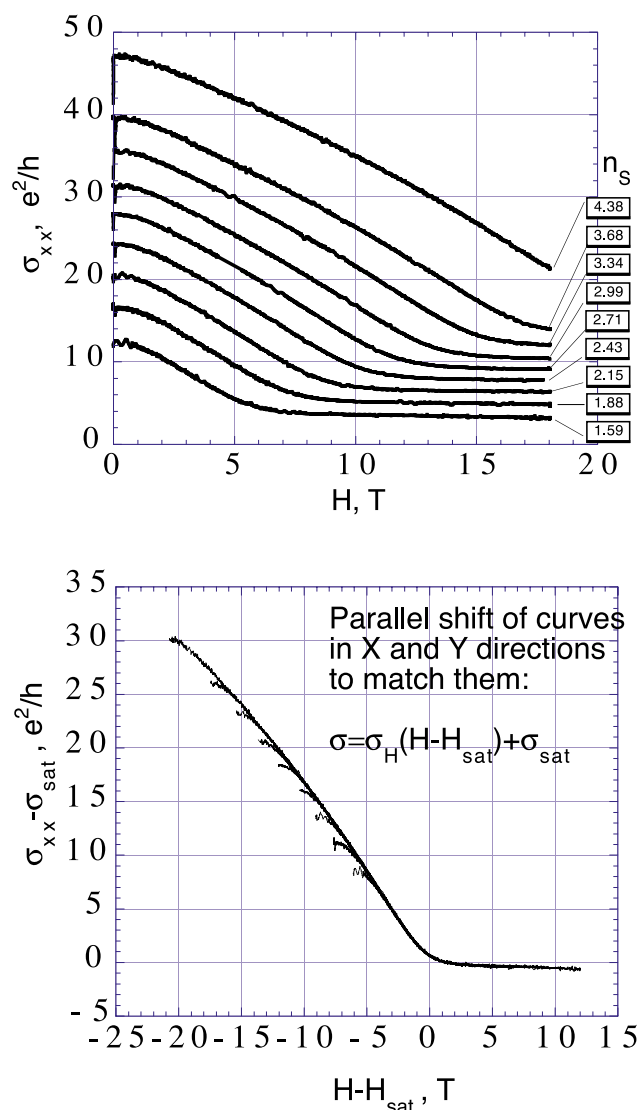


Figure 1. (a) Conductivity $\sigma(n, H)$ versus in-plane magnetic field at different electron densities n in units 10^{11}cm^{-2} as labeled. Data are shown for sample #3 at $T=100 \text{ mK}$. (b) Data collapse obtained by applying simple shifts along the x axis by an amount H_{SAT} and the y axis by σ_{SAT} , such that $\sigma(n, H) = \sigma_H(H-H_{\text{SAT}}) + \sigma_{\text{SAT}}(n)$.

The universal function $\sigma_H(H-H_{\text{SAT}})$ goes to ≈ 0 above H_{SAT} , the magnetic field above which the electron system is spin polarized completely.^{1,2} The existence of such a universal function $\sigma_H(H-H_{\text{SAT}})$ raises the possibility that the magnetic field-dependent portion of the conductivity is determined by the *overlap* of spin-up and spin-down electron subbands.

Shubnikov-de Haas oscillations were measured in fixed high magnetic fields as a function of the angle θ between the sample plane and the magnetic field

for small values of θ and different electron densities. The results yield the net spin polarization of the system.

Acknowledgements: The authors wish to thank Tim Murphy and Eric Palm for help with the experiment. This work was supported by DOE grant No. DOE-FG02-84-ER45153. Partial support was also provided by NSF grant DMR-9803440.

¹ Okamoto, T., *et al.*, Phys. Rev. Lett., **82**, 3875 (1999).

² Vitkalov, S.A., *et al.*, Phys. Rev. Lett., **85**, 2164 (2000).

Spin-Spin Interaction Observed by Zeeman Spectroscopy in GaAs-AlGaAs Quasi-Zero-Dimensional Quantum Structure

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The spin-spin interaction in low-dimensional quantum structures has been attracting interest with numerous theoretical projections of its usefulness in a practical system of quantum computation,^{1,2,3} since the electronic or nuclear 1/2 spin state provides two quantum bit or “qubit,” quantum Boolean states, and the interaction provides the needed stability and switching time. One of the outstanding candidates for a qubit is a quantum dot (QD), which has the spin level separation larger than thermal excitation with a high degree of quantum coherence and the presence of transient Heisenberg coupling of

$$H_s = J(t)\vec{S}_1 \cdot \vec{S}_2$$

In this work, we report the Zeeman results of narrow GaAs-Al_{0.5}Ga_{0.5}As quantum wire arrays (QWR) in magnetic fields ranging from 0 to 30 T. The Zeeman splittings are obtained from the separation between σ^+ and σ^- peaks in polarization-dependent photoluminescence (PPL) at liquid He temperature. In this experimental arrangement, the electron is

confined in one-dimension (1-D) in low field, but exhibits quasi-0-D confinement in high field. The sharp change of the slope occurs around B_c . The data of $B_a > B_c$ is best fit with $\Delta E = \mu_B g_L B + n\mu_B g_s B + n\epsilon$, where g_L is g-factor for $B_a < B_c$, $g_s \sim 1$, $\epsilon \sim 0.6$ meV, and $n=1$ or 2, depending on where the exciting laser spot hits the sample. At the vicinity of B_c , the radius of the Landau orbit is equal to the exciton Bohr diameter.

The results for $B_a > B_c$ suggest that the exciton is coupled with a magnetic dipole, which is believed to be electron spin, as the electron becomes more tightly confined by the applied field. The observed magnitude of zero-field splitting obtained from the extrapolation of $B_a > B_c$ data is larger than $k_B T$ for liquid He, and is equivalent to $\tau_s = \hbar/\Delta E \sim 7$ ps, where τ_s is the switching time. The decoherence time estimated from the spectral line width, τ , is 0.2 ps.

If the observed result is a characteristic of 0-D quantum confinement, the zero-field splitting of ground states $|J\uparrow\rangle|S\downarrow\rangle$ and $|J\downarrow\rangle|S\uparrow\rangle$ may provide an actual qubit level with σ^+ and σ^- optical control. In conclusion, the study of spin states under quasi-0-D quantum confinement provides a positive prospect that a quantum dot can be a candidate for a practical qubit system.

Acknowledgements: This work was supported in part by the BK-21 project of the Ministry of Education, Korea.

¹ Charles, H., *et al.*, Nature, **404**, 247 (2000).

² Loss, D., *et al.*, Phys. Rev. A, **57**, 120 (1998).

³ Bondadeo, N.H., Science, **282**, 1473 (1998).

Theoretical Study of Crystalline Ordering in Partially Filled Landau Levels

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Recently, there is considerable interest in crystalline ordering in two-dimensional (2D) electron gas systems subject to a strong perpendicular magnetic field, inspired by the recent experimental evidence

of charge-density-wave ordering in partially filled high Landau levels, both near and away from half-filling.¹ In our earlier work,² we have studied half-filled high Landau levels numerically using exact diagonalization of finite size systems. In these studies, we diagonalize the Hamiltonian of finite size systems with the number of electrons equal to one-half that of the number of orbitals in the partially filled Landau level, neglecting the mixing of different Landau levels. Typically, we study systems containing 6 to 12 electrons. Our results strongly suggest that 1D CDW (stripes) are formed in the ground state.²

In the past year, we have extended these studies in two directions:

(i) We have performed exact diagonalization studies of partially filled high Landau level *away* from half-filling. We have found that for Landau level indices equal or above 2, and filling factors below 0.4 or above 0.6 (and not too close to 0 or 1), the ground state of the systems has two-dimensional crystalline order, in which electrons form “bubbles” with more than one electrons, and these bubbles in turn form a two-dimensional periodic structure. This conclusion is based on the following findings: (a) We find the density response function $\chi(\mathbf{q})$ is sharply peaked at a two-dimensional array of wave vectors \mathbf{q}_n . (b) The ground state density-density correlation function is also peaked at these wave vectors. (c) There exist a manifold of low-energy excited states that are nearly degenerate with the ground state; the degeneracy and quantum numbers of this manifold are consistent with formation of periodic structure made of bubbles. Our results agree well with the predictions of earlier Hartree-Fock theory, and recent transport measurements that suggest the existence of a depinning field near filling factor $2+1/4$ (see Cooper *et al.* in Ref. 1). These results have been published recently.³

(ii) We have also studied the formation of Wigner crystal in lowest Landau level, at very low filling factors, using similar methods. Our results suggest that for bare Coulomb interaction, and without effects like Landau level mixing and finite layer thickness, Wigner crystals start to form near filling factor $1/7$. Currently, we are studying the nature of the phase transition between the Wigner crystal phase and the

quantum Hall phase at filling factor $1/7$, as well as the effect of disorder on the former.

¹ Lilly, M.P., *et al.*, Phys. Rev. Lett., **82**, 394 (1999); Du, R.R., *et al.*, Solid State Commun., **109**, 389 (1999); Pan, W., *et al.*, Phys. Rev. Lett., **83**, 820 (1999); Cooper, K.B., *et al.*, Phys. Rev. B, **60**, R11285 (1999).

² Rezayi, E.H., *et al.*, Phys. Rev. Lett., **83**, 1219 (1999).

³ Haldane, F.D.M., *et al.*, Phys. Rev. Lett., **85**, 5396 (2000).

High Magnetic Field Microwave Conductivity of 2D Electrons in an Array of Antidots ▀IHRP▀

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We have studied microwave conductivity, $\text{Re}(\sigma_{xx})$, of a high mobility two-dimensional electron system (2DES), patterned with an array of antidots, for frequency between 0.05 and 10 GHz in high magnetic fields. The antidot array, a 500 nm square lattice of 50 nm lithographic diameter holes, was fabricated in the slots of planar microwave transmission lines, whose loss was measured to determine $\text{Re}(\sigma_{xx})$. At the lowest frequencies the measured conductivity is what would be expected from dc experiments, with well-developed fractional quantum Hall effect minima and a small (10 percent) peak from composite fermion scattering around $\nu=1/2$. For f above about 2 GHz, over a broad range of ν , we find strongly increasing $\text{Re}(\sigma_{xx})$, vs. f in a broad region of B centered around $\nu=1/2$. This frequency response is unobservable above about 0.5 K, and grows more pronounced as the temperature is decreased, down to 100 mK, the lowest temperature at which we measured. This unexpected enhancement of microwave conductivity is absent in a sample from the same wafer but without the antidots, and may be due to excitations of the antidot edges.

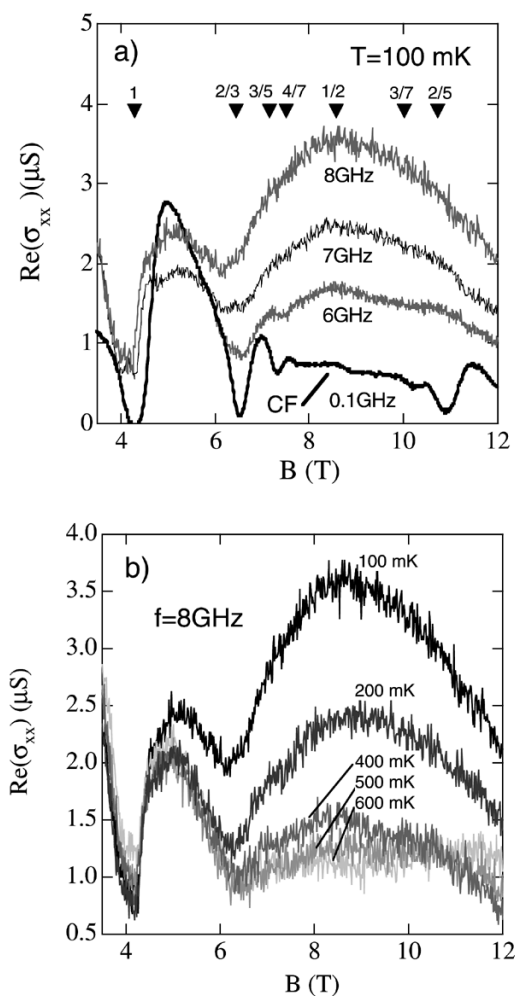


Figure 1. (a) Measured microwave conductivity, $\text{Re}(\sigma_{xx})$, plotted against magnetic field, B , for a sample patterned with an antidot lattice constant $a=500$ nm. Solid triangles mark the Landau level filling factors, ν . (b) $\text{Re}(\sigma_{xx})$, vs. B with $f=8$ GHz, various temperatures.

Magnetic Field and Density Dependence of Microwave Resonance in a 2D Electron System at Low Filling Factor ▀ IHRP ▴

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We have studied microwave conductivity, $\text{Re}(\sigma_{xx})$, of a high mobility two-dimensional electron system (2DES), for frequency (f) between 0.05 and 10 GHz.

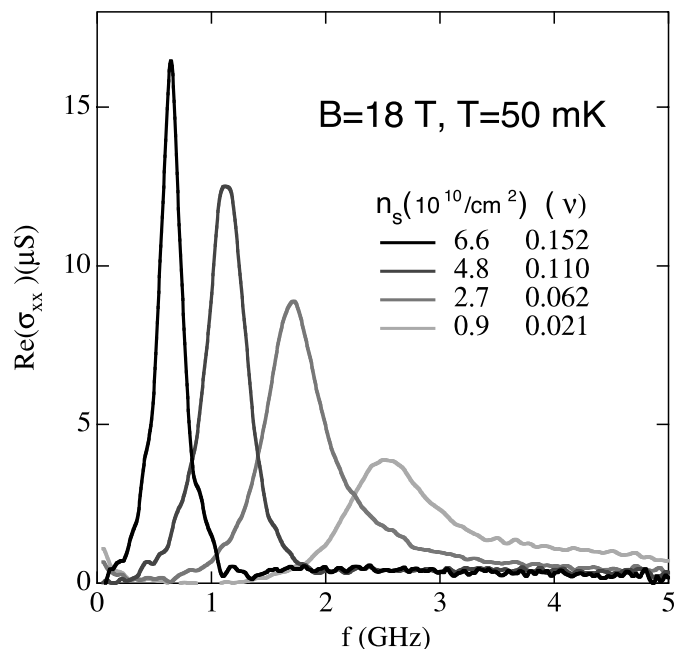


Figure 1. Real part of diagonal conductivity $\text{Re}(\sigma_{xx})$, vs. frequency at various carrier densities, n_s , at a constant magnetic field of 18 T, $T=50$ mK.

Carrier densities (n) as low as $5.0 \times 10^9/\text{cm}^2$ were produced by applying a back gate voltage, resulting in values of the Landau level filling factor, ν , down to 0.01 at the maximum B of 20 T. Without back gate voltage, the 2DES had carrier density, n_s , of $6.6 \times 10^{10}/\text{cm}^2$, and mobility $5.0 \times 10^6 \text{ cm}^2/\text{Vs}$.

In the high B insulating phase of high quality 2DES, there is generally a microwave spectral line thought to be due to a pinning mode of a Wigner crystal. In this sample, unlike in higher disorder 2DES,¹ the resonance only appears for $n < 1/5$. As shown in the Fig. 1, the microwave resonance remains well-defined and shifts to higher peak frequency f_{pk} as n is reduced. This increase of f_{pk} vs. n is seen over the entire magnetic field range in which the resonance appears, and can be interpreted² as evidence for weak pinning in a Wigner crystal. Strikingly, at each density we examined, f_{pk} vs. B exhibits a maximum, and so decreases at the highest magnetic fields.

¹ Engel, L.W., *et al.*, Solid State Commun., **104**, 167 (1997).

² Li, C.-C., *et al.*, Phys. Rev. B, **61**, 10905 (2000).

Thermopower in Half-Filled Landau Levels in a Square Quantum Well

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It is now well-known that the magnetotransport at the Landau level filling factor $\nu=1/2$ in a quantum Hall system can be understood in terms of the formation of a composite Fermion Fermi surface.¹ However, a strong deviation from the characteristic composite Fermion transport could result for a thick quantum Hall system, where the thickness of the electron layer far exceeds the magnetic length. For example, in a 35 nm square GaAs/AlGaAs quantum well (QW), the magnetoresistance exhibits a sharp, strongly temperature dependent minimum at $\nu=1/2$,² in contrast to the resistance features observed typical of regular heterojunctions. Studies of thermal transport in this system will help to elucidate the origin of such resistance features. We have pursued thermopower, S_{xx} , in the same QW system, up to a magnetic field ~ 33 T, and at sample temperatures $T > 200$ mK. The QWs have a mobility $\mu \approx 3.5 \times 10^6 \text{ cm}^2/\text{Vs}$ and an electron density $n \approx 3.6 \times 10^{11}/\text{cm}^2$. The QW sample, heater, and RuO₂ thermometers (see inset, Fig. 1) are sealed in an epoxy vacuum can, which is in turn immersed in the ³He/⁴He mixture of a dilution refrigerator. Fig. 1 shows S_{xx} at high magnetic field for several temperatures. The S_{xx} exhibits deep minima at the fractional filling factors $\nu=2/3$, $3/5$, and $4/7$, as well as integer $\nu=1$, in keeping with the formation of an energy gap for the quantum Hall states. On the other hand, the S_{xx} at $\nu=1/2$ exhibits a broad maximum down to $T \sim 200$ mK, apparently consistent with the results reported for heterojunctions.³ Measurements of thermopower at $\nu=1/2$ and $3/2$ at lower temperatures, $T < 100$ mK, as well as those in half-filled high Landau levels, $\nu=5/2$, $7/2$, $9/2$, and $11/2$ are planned at the NHMFL.

Acknowledgements: This research is supported by NSF DMR-9705521.

- ¹ Perspectives in Quantum Hall Effect - Novel Quantum Liquids in Low-Dimensional Semiconductor Structures, ed. by S. Das Sarma and A. Pinczuk, Wiley and Sons, New York, 1997.
- ² Du, R.R., *et al.*, 1999 NHMFL Annual Research Review, p.120.
- ³ Tieke, B., *et al.*, Phys. Rev. Lett., **76**, 3630, (1995); Bayot, V. *et al.*, Phys. Rev. B, **52**, 8621, (1995).

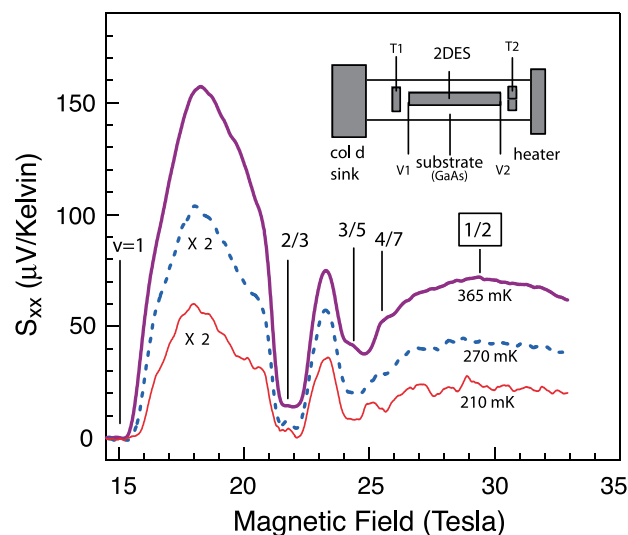


Figure 1. The thermopower, S_{xx} , at the integer $\nu=1$, and the fractional $\nu=2/3$, $3/5$, and $4/7$ Landau level filling factors, as well as $\nu=1/2$, measured in a 35 nm GaAs/AlGaAs quantum well sample at several temperatures in high magnetic field up to 33 T.

